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Integrated Climate Assessment for Army Enterprise Planning

Projections of Climate Impacts and Extremes for Sites in the Continental United States

John W. Weatherly

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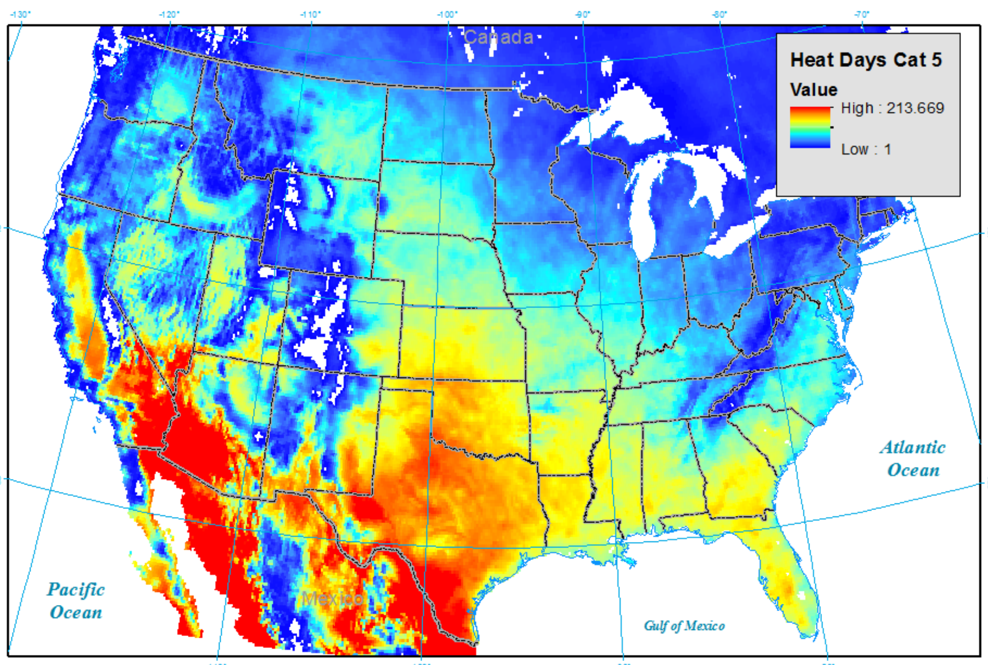

Number of Days annually with wet bulb-black globe temperature (WBGT) greater than 32 °C (90 °F) for projected climate in 2070-2099. Daily climate projections over 12 global climate models from the Intergovernmental Panel on Climate Change's high-emission greenhouse gas scenario.

Projections of Climate Impacts and Extremes for Sites in the Continental United States

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Final Report

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Abstract

Increasing temperatures and changes in precipitation associated with climate change are expected to have increasing impacts on the contiguous United States in the coming decades, including impacts on military training and outdoor activities in general. This work used projections of daily temperature and precipitation from multiple global climate model projections to calculate the days with high heat and drought indices, extreme high- and low temperature and precipitation event days, and heating and cooling degree-day indices. The heat stress index (the wet bulb black globe temperature, or WBGT) and Keetch-Byram drought index are calculated from climate model projections from 1950-1999 and 2070-2099, and compared to projections calculated from observed weather data for stations across the contiguous United States. Results showed that significant increases are projected across the southern United States for the days in the high heat category above 32 °C (90 °F). The higher humidity of the southeastern United States contributes to high WBGT as well, while the air temperatures are greatest in the southwest. These projected impacts can be characterized as widespread and severe for large portions of the United States, with expected impacts to military planning, public health and safety, and natural resource management.

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Preface

This study was conducted for Headquarters, U.S. Army Corps of Engineers (HQUSACE) under Project 622720A896, "Environmental Quality Guidance," Work Package "Integrated Climate Assessment for Army Enterprise Planning," Work item L4F5G1, "Forecast Future Climate/Weather." The technical monitor was Ms. Sarah Harrop, Headquarters, Department of the Army (HQDA).

The work was performed by the Terrestrial and Cryospheric Sciences Branch (CEERD-RRG) of the Research and Engineering Division (CEERD-RR), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. John Weatherly was Chief, CEERD-RRG, and Mr. J. D. Horne was Chief, CEERD-RR. The Deputy Director of ERDC-CRREL was Mr. David B. Ringelberg, and the Director was Dr. Joseph L. Corriveau.

COL Ivan P. Beckman was Commander of ERDC, and Dr. David W. Pittman was the Director.

1 Introduction

1.1 Background

Increasing surface air temperatures associated with anthropogenic climate change are expected to have growing impacts on the operation and soldier training at U.S. Army installations and training ranges in the coming decades. Projections from global climate models (GCMs) include annual average surface air temperature increases between 3 and 6 °C (5.4 and 10.8 °F) for the contiguous United States through year 2100 for multiple greenhouse gas emission scenarios (IPCC 2013). Regional precipitation change projections vary from decreasing precipitation in the southwest United States to increasing precipitation in the southeast and northern United States. However, these projections vary considerably among different GCMs (IPCC 2013).

These trends have the potential to affect soldier training, daily operations, and environmental resource management at U.S. Army installations. Daytime training hours on installations and training ranges are particularly sensitive to increasing maximum daily temperature and heat index, as there are significant risks to soldier health and safety from high temperatures, humidity, and solar exposure. Current U.S. Army medical guidance (2003) prescribes specific ratios of solder training work rates, rest, and recommended water intake based on WBGT, which combines the air temperature, humidity (via the wet bulb temperature), and solar exposure (black globe temperature).

The evaluation of WBGT and drought index from observations and GCMs used in this work have been published in Weatherly and Rosenbaum (2017); this work expands these results to include other extreme climate impacts of high temperature, freeze-thaw transitions, heating and cooling-degrees, and high- and low-precipitation days. Additional previous published climate studies have demonstrated these types of impacts:

- Dunne et al. (2012) analyzed the potential loss in labor hours due to high WBGT in the historical climate data and in climate projections of the Earth System Model (ESM2M) of the Geophysical Fluid Dynamics Laboratory (GFDL). They found reductions of 80% in labor hours during the warmest months for the high-emission scenario through 2100,

consistent with WBGT above 32.2 °C (90 °F), i.e., the "black" Category 5 restrictions of 10 minutes work and 50 minutes rest per hour.
- Pal and Eltahir (2016) used a wet bulb temperature threshold of 35 °C (95 °F) as the limit of human adaptability, and projected future climate scenarios for southwest Asia (Arabian Peninsula and surrounding region) exceeding this limit, and temperatures exceeding 45 °C (113 °F) through June-July-August for high-greenhouse gas scenarios in the 2070-2100 timeframe.

These projected impacts are expected to be similar across many GCMs, as the projected temperature changes are largely consistent for future scenarios.

1.2 Objective

The objective of this work was to document the analysis of projected impacts of future climate change scenarios on U.S. Department of Defense (DoD) installations and regions in the contiguous United States. These impacts include the limitations on soldier training due to excessive heat and high humidity, high drought conditions associated with high fire risks on training lands, and other climate indices such as the heating degree days (HDD) and cooling degree days (CDD) for installations.

1.3 Approach

Climate projections were taken from GCM scenarios from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC 2013) for increasing greenhouse gases from the mid-20th century through the 21st century. The heat and drought indices derived from downscaled GCM projections were compared to those derived from observed climate data from both municipal and military stations across the contiguous United States. This work assessed how these climate impacts could affect the training mission for the U.S. Army (under the assumed future projections), and what types of adaptations and training schedules may have to be made if these climate changes become reality.

There is no certain predictive basis to determine what changes to the current trend the future emissions path may take, based on unknown future mitigation actions or policy decisions. Extrapolation from current rising emission rates (sometimes considered as the "business-as-usual" scenario) may be considered the "default" choice, as it assumes no changes from the recent trajectory, and it also represents the upper limit or worst-case scenario of the representative concentration paths (RCPS) considered. For this reason, this study focuses on the projections from the high-emission scenario (called RCP 8.5, see below), as it represents the extrapolated trends in greenhouse gas emission most closely.

As described in earlier technical reports for this project (Weatherly and Rosenbaum 2015) the greenhouse gas emission scenarios created by the scientific community and used by the GCMs use different potential timelines of future greenhouse gas emissions and their resulting concentrations in the atmosphere through the year 2100. The creators of the scenarios used in the Intergovernmental Panel on Climate Change's (IPCC's) Fifth Assessment Report (IPCC 2013) and in the Coupled Model Intercomparison Project (CMIP) version 5 GCMs were labeled to reflect increasing RCPs for emissions, leading to the equivalent increase in infrared radiative forcing at the surface, in particular:

- RCP 2.6: Emission path leading to 2.6 W m^{-2} radiative forcing (lowest-emission scenario)
- RCP 4.5: Emission path leading to 4.5 W m-2 radiative forcing (moderate low-emission scenario)
- RCP 6.0: Emission path leading to 6.0 W m-2 radiative forcing (higher medium-emission scenario)
- RCP 8.5: Emission path leading to 8.5 W m-2 radiative forcing (business-as-usual high-emission scenario).

1.4 Scope

This study is the product of a U.S. Army research program to study the potential impacts of future climate change on training, installations, and natural resources. However, these potential impacts also would affect public, agricultural, and municipal activities in addition to military operations.

Future climate changes used in this study are based on possible scenarios of greenhouse gases and associated global-scale climate trends. These are not "predictions" in the sense that they make forecasts based on what is expected to occur with some measurement of skill and certainty. Nevertheless, the term "projections" is used here because many possible future emissions paths are possible.

2 Data and Models

2.1 Climate data and climate model projections

The indices of heat stress, fire risk, and other extremes for the contiguous United States were calculated from two types of data: observational station data and GCM simulations of past and future climate projections. The observed station data used were taken from the Global Summary of the Day archive from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center from the years 1950-1999. These data include daily mean, maximum, minimum temperatures, mean dew-point temperature, wind speed, cloud cover, and precipitation. The station data used here were recorded at municipal airports, military airfields, and other U.S. locations. Figure 2-1 shows the names and locations of the stations used in this study, including the following military installations: Fort Benning, GA; Fort Stewart, GA; Hill Air Force Base (AFB), UT; Dugway Proving Ground, UT; and Joint Base Lewis-McChord, WA. The map shown in Figure 2-1 is divided into the seven regions used in this study: (1) Southwest (SW), (2) Northwest (NW), (3) Southern Great Plains (SGP), (4) Northern Great Plains (NGP), (5) Southeast (SE), (6) Great Lakes (GL), and (7) Northeast (NE).

Figure 2-1. Locations within the United States for which observed climate data and downscaled daily climate projections were analyzed. The seven larger regions are defined as Southwest (SW), Northwest (NW), Southern Great Plains (SGP), Northern Great Plains (NGP), Southeast (SE), Great Lakes (GL), and Northeast (NE).

The GCM-based climate projections used in this study are the bias-corrected constructed analogs (BCCA) of daily maximum and minimum temperatures and daily precipitation of Reclamation (2013) derived from GCM simulations in the CMIP-5 (version 5) archive that supports the IPCC's Fifth Assessment Report (2013). The method of producing the BCCA data is described in detail in Maurer et al. (2007) and Reclamation (2013), and can be summarized by:

- Step 1, the regridding of the each GCMs' output to a common 2 by 2 degrees (latitude-longitude) grid over the continental United States.
- Step 2, bias-correction by adjusting the GCM temperatures and precipitation so the mean, variance, and quartiles of the frequency of daily maximum and minimum temperatures and precipitation match the observed historical data for 1950-1999 on the 2-degree grid. While the bias-correction eliminates the mean differences between the GCMs and the historical data over 1950-1999, the individual years simulated by the GCMs do not match individual observed years.
- Step 3, the spatial disaggregation of the 2 by 2-degree data down to a ⅛ by ⅛ degree grid, which can also introduce small differences from the observed means on the 2 scale. Downscaled BCCA projections from 12 GCMs (Table 2-1) were used. The downscaled GCM simulation data from 1950-1999 were taken the historical climate scenario, and projections for years 2070-2099 (Table 2-2) were taken from the CMIP-5 RCP 8.5 scenario, the high-emission scenario with an effective radiative forcing increase of 8.5 W m^{-2}.

Table 2-1. List of GCMs whose downscaled BCCA projections are used in this study.

Model Name	Institutions
BCC-CSM1.1	Beijing Climate Center, China Meteorological Administration
CanESM2	Canadian Centre for Climate Modelling and Analysis
CNRM-CM5	Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique
ACCESS1.0	CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia), and BOM (Bureau of Meteorology, Australia)
CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence
INM-CM4	Institute for Numerical Mathematics
IPSL-CM5A-LR	Institut Pierre-Simon Laplace
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology
MPI-ESM-LR	Max Planck Institute for Meteorology (MPI-M)
MRI-CGCM3	Meteorological Research Institute
CCSM4	National Center for Atmospheric Research
GFDL-CM3	Geophysical Fluid Dynamics Laboratory

Table 2-2. Projected mean, minimum, and maximum changes in temperature (°C) and precipitation (%) between the historical BCCA (1950-1999) and RCP 8.5 (2070-2099) across the 12 GCMs over the seven regions.

Region	ΔT (°C) mean/min/max	ΔP (%) mean/min/max
SW	4.6 / 2.4 / 5.5	-3.3 / - 10 / - 1.2
SGP	4.5 / 2.5 / 5.5	-1.3 / -8.2 / + 4.1
SE	4.2 / 2.1 / 5.0	8.2 / - 9.1 / +18
NW	3.2/ 2.0 / 3.9	11.2 / 2.3 / + 19
NGP	3.4 / 2.1 / 4.3	-5.3 / -8.5 / 5.7
GL	3.8 / 2.1 / 4.5	-4.2 / - 11 / 12
NE	3.5 / 2.5 / 4.3	12.3 / 3.1 / 19

2.2 Heat stress index – Wet bulb black globe temperature

The first two climate indices considered here that reflect potential impacts on military installations and resources are: (1) the number of days with high heat index and (2) the number of days with high drought index. The heat index used here (the WBGT) is used by the U.S. Army to regulate work/rest restrictions based on heat risks to soldiers in training, as listed in Table 2-3. WBGT Categories 1 through 5 correspond to WBGT increasing from 25.6 °C (78 °F, Cat 1) to >32.2 °C (>90 °F, Cat 5). The Army also uses the other drought index, the Keetch-Bryam Drought Index (KBDI), to evaluate risks of fire ignition on training ranges to ensure that adequate fire-fighting resources are available (Table 2-3). These two indices are both computed from daily temperature, precipitation, and other observed station data, and are also be computed from the climate model projection of climate scenarios.

Table 2-3. Heat Category table using WBGT for training work-rest times and water intake based on Department of the Army TB MED 507 (2003).

Heat Category	WBGT Index, F°	Easy Work		Moderate Work		Hard Work	
		Work/Rest	*Water Intake (Qt/H)*	*Work/Rest*	*Water Intake (Qt/H)*	*Work/Rest*	*Water Intake (Qt/H)*
1	78° - 81.9°	NL	½	NL	¾	40/20 min	¾
2 (GREEN)	82° - 84.9°	NL	½	50/10 min	¾	30/30 min	1
3 (YELLOW)	85° - 87.9°	NL	¾	40/20 min	¾	30/30 min	1
4 (RED)	88° - 89.9°	NL	¾	30/30 min	¾	20/40 min	1
5 (BLACK)	> 90°	50/10 min	1	20/40 min	1	10/50 min	1

The number of heat-restricted training days are computed from daily WBGT, which combines the wet bulb temperature (Twb), ambient air temperature (Tair), and temperature measured inside a black globe in the incident sunlight (Tg):

$$WBGT = 0.7\ Twb + 0.2\ Tg + 0.1\ Tair \tag{1}$$

While the WBGT can be measured onsite at installations, it is more often computed from the observed air temperature (Tair), relative humidity, and estimates of black globe temperature Tg. This study calculated the daily maximum and minimum daily WBGT using the maximum and minimum observed dry bulb temperature and daily dewpoint temperature (which usually changes little through the day) to obtain the relative humidity (RH) coinciding with both maximum and minimum temperatures. The graphical method for determining the wet bulb temperature, Twb, from the ambient dry bulb air temperature and relative humidity can be performed using a meteorological skew-T diagram. For repeated calculations, a table for Twb values was created for the range of temperature and humidity present for the locations considered. Chapter 3 of this report describes the impacts on WBGT of changing relative humidity relative to temperature for these locations.

The black globe temperature (Tg) is estimated using the formula by Dimiceli et al. (2011), with an algorithm based on measurements inside a sunlit globe with surface albedo of 0.05 and emissivity 0.95. Their derived formulation is:

$$Tg = (\ B + CTair + 7680000) / (C + 256000) \tag{2}$$

$$B = S\ (\ fdirect / (4\ \sigma \cos z) + 1.2 * fdiffuse/ \sigma\ ) + \varepsilon\ Tair4 \tag{3}$$

where:

S is the surface solar irradiance in W m-2
fdirect and fdiffuse are the fractional direct
diffuse radiation, σ, is the Stefan-Boltzmann constant
cos z is the cosine of the solar zenith angle z
ε is the atmospheric emissivity (assumed =1).

The other term is:

$$C = h\ u\ 0.58 / 5.38 \text{ x}10\text{-}8 \tag{4}$$

where:

h = 0.1
u = the wind speed in meters per hour.

For the parameters for direct and diffuse fractions of solar irradiance that are not recorded in the NOAA daily data, fdirect = 0.7, fdiffuse = 0.3, and:

$$S = Smax \cos Z \tag{5}$$

where:

Smax = the maximum solar irradiance
Z = the solar zenith angle at the site's latitude φ, at the solar declination angle δ (23.6 degrees N on the summer equinox) at local solar noon, and:

$$\cos Z = \sin \varphi \sin \delta + \cos \varphi \cos \delta \tag{6}$$

The maximum solar irradiance Smax varies widely between locations and with atmospheric conditions. The monthly mean of the maximum daily irradiance from the closest stations in the U.S. Climate Reference Network (Diamond et al. 2013) was used for Smax for the locations. The maximum daily temperatures usually occur later in the day than does the maximum irradiance.

2.3 Drought/fire-risk index

The KBDI, designated Q, is calculated by incrementing the index dQ using the daily maximum air temperature (Tmax) and daily precipitation, P. The formulation follows the revised and corrected English units equation of Alexander (1990) and Crane (1982) of the original Keetch and Byram (1968) index:

$$dQ = \frac{[800-Q][0.968\exp(0.0486Tmax) - 8.30]dt\ x\ 10^{-3}}{1+10.88\exp(-0.0441R)} \tag{7}$$

The minimum Q value is kept at zero and the maximum at 800, which indicates a 0.20 m (8 in.) deficit in precipitation.

The risk of igniting fires on training ranges through live-fire training potentially increases with greater KBDI, i.e., with greater maximum daily temperatures and little or no precipitation (Table 2-4). The KBDI increases with duration of days with no precipitation, to its maximum value of 800. For any particular training range, there are other potential factors to consider in determining the risk of igniting fires through live-fire training, such as the presence or abundance of dry vegetation, and persistent wetlands that may not be at risk for ignition. Therefore, the onsite determination of fire risk by firing range managers and restrictions on live-fire training are determined locally and are not based on a single factor such as KBDI.

Table 2-4. Fire danger categories with live-fire training restrictions and fire-fighting requirements, with the KBDI range used in this study for each category.

Fire Danger Condition	Expected Fire Behavior	Training Restrictions	Fire-Fighting Detail Requirements	Derived KBDI*
GREEN	Fires are difficult to start and do not burn with vigor. Fires can easily be controlled using direct attack.	None.	None.	0-300
AMBER	Fires start easily and may burn quickly through grass and shrub fuels. Fires can be controlled using direct attack, but in some circumstances may require indirect attack methods.	No aerial flares outside the live-fire training areas. Pyrotechnics must be used on roadways, tank trails, or barren areas.	None.	300-600
RED	Fires start easily, move quickly, burn intensely, and may be difficult to control.	No pyrotechnics, incendiary munitions, tracers.	10-person fire-fighting detail required. On-call helicopter required on 20-minute standby.	600-750
BLACK	Fires start very easily and are impossible to control.	No live-fire training. No pyrotechnics. Non-live-fire training must be authorized by the Senior Mission Commander.	None.	750-800

2.4 Extreme temperature, precipitation, and heating and cooling degree-days

The same BCCA climate projection data described above are also used to calculate a number of other simple climate indices that are relevant to Army installations, training, and natural resources (Table 2-5). These indices, listed below, are calculated for the CONUS-wide climate data for the observations for 1950-1999, and for the future projections for 2070-2099. This work presents the future projections from the high-emission RCP 8.5 scenario, and also the calculated lower-emission projections (RCPs 2.6 and 4.5).

Table 2-5. Climate and extreme indices calculated from the CONUS observed data and climate projections.

Climate Index	Definition	Potential Impact
Heating Degree-Days	Accumulated annual total of days * daily mean temperature difference below 18 °C (65 °F)	Installation heating energy demand and cost
Cooling Degree-Days	Accumulated annual total of days * daily mean temperature difference above 18 °C (65 °F)	Installation cooling energy demand and cost
Growing Degree-Days	Accumulated annual total of days * daily mean temperature difference above 10 °C (50 °F)	Potential growth in resorting vegetation on ranges (incl. agriculture crops and invasive plants)
# Days with Freeze/Thaw	Temperature crosses 0 °C (32 °F) (up or down) on consecutive days	Roadway and vehicle damage, slope erosion
# Days T_{max} >100 °F	Average days per year with T_{max} >100 °F	Training days, power peak demand, roads and railroad weight limits
# Days T_{max} >95 °F	Average days per year with T_{max} >35 °C (95 °F)	Training days, power peak demand, roads and railroad weight limits
# Days T_{min} <10 °F	Average days per year with T_{min} <-12 °C (10 °F)	Training days, peak heating, utility freeze damage
# Days P >2 in.	Average days per year with daily precipitation P>2.0 in.	Potential flood, erosion damage in maneuvers
# Days P <0.01 in.	Average days per year with daily precipitation P<0.01 in.	Water supply restrictions, vegetation water stress

Chapter 3 of this report gives the results of many (but not all) of these indices, with the relative change between observed historical climate data and potential future climate projections from the GCMs. These indices have also been mapped and stored as digital Geographic Information System (GIS) data layers that can be loaded into software such as ArcGIS for added to other maps of Army installations and other CONUS locations such as roadways, cities, and natural resources.

3 Results of Climate Impact Projections

3.1 Heat stress

The impacts of extreme heat stress on the Army training mission is one of the most directly computable impacts from weather and climate. The heat index used here is the WBGT, which includes the effects of the daytime air temperature, humidity, solar radiation, and wind (as a cooling factor) to determine the training-restriction category.

Table 3-1 lists the days with WBGT in each heat-restriction category for the observed stations (OBS), for the historical period from the GCMs (HIST) and for the future climate projections from RCP 8.5 for 2070-2090. Figure 3-1 shows these data as bar graphs for each station, and Figure 3-2 shows them as CONUS-wide maps.

The highest Category 5 days (WBGT >32 °C [90 °F]) increases by 27 days in the Southwest, 55 days in the Southern Great Plains, and 75 days in the Southeast. This reflects the role of greater relative humidity (on top of the temperature change) in the Southeast in the observed data, and drier conditions in the Southwest. The northern regions have smaller changes, and not as many high WBGT days with training restrictions.

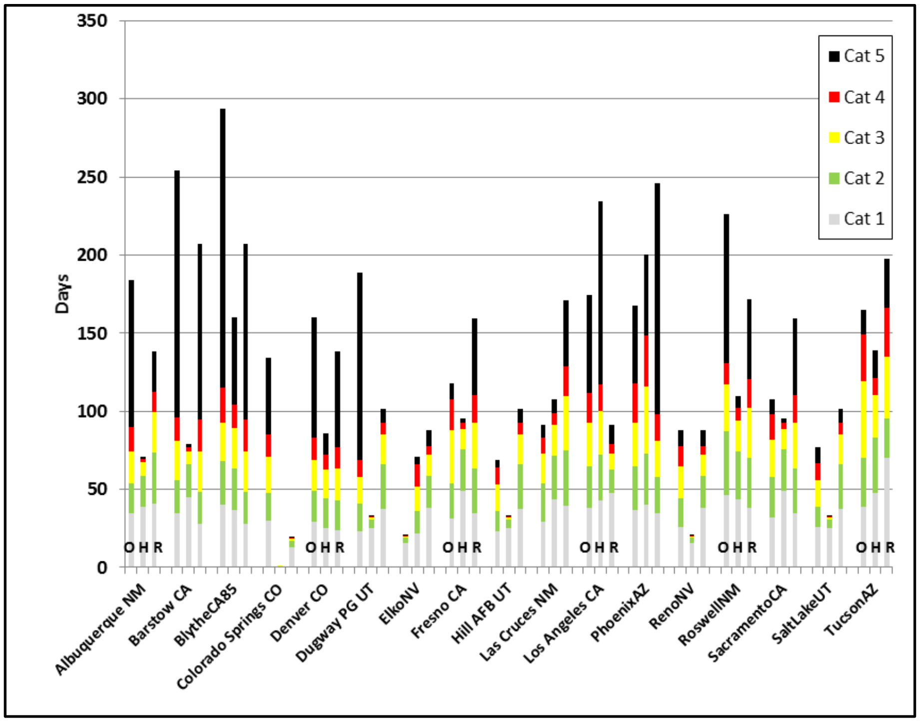
Table 3-1. Number of days annually with daily maximum WBGT in each category, using the OBS and historical BCCA (HIST) for 1950-1999, and RCP 8.5 for 2070-2099, averaged over all 12 GCMs for the station locations in the seven U.S. regions, and the inter-model mean, minimum and maximum difference in WBGT days between HIST and RCP 8.5.

	1950-1999	1950-1999	2070-2099	mean / min / max
SW	*OBS*	*HIST*	*RCP 8.5*	*Δ (RCP - HIST)*
Cat 5	56.1	16.9	43.8	27 / 19 / 35
Cat 4	15.4	7.6	13.4	5.8 / 1 / 19
Cat 3	23.4	14.5	22.4	7.8 / 0 / 25
Cat 2	21.9	19.4	24.4	5.0 / 1 / 10
Cat 1	31.5	33.9	36.6	2.7 / -4 / 15
SGP	*OBS*	*HIST*	*RCP 8.5*	*RCP - HIST)*
Cat 5	33.3	31.6	87.0	55.4 / 21 / 65
Cat 4	22.7	15.3	18.6	3.3 / 1 / 10
Cat 3	40.3	28.3	27.6	-.8 / -4 / 12
Cat 2	38.3	28.9	26.2	-2.7 / -5 / 4
Cat 1	47.3	45.7	33.4	-12.2 / -25 / -2

	1950-1999	1950-1999	2070-2099	mean / min / max
SE	*OBS*	*HIST*	*RCP 8.5*	*Δ (RCP - HIST)*
Cat 5	38.9	18.8	93.9	75.1 / 32 / 90
Cat 4	31.1	23.5	23.4	-.2 / -10 / 12
Cat 3	50.9	40.9	32.4	-8.6 / -12 / 3
Cat 2	41.4	37.0	29.4	-7.6 / - 15 / -2
Cat 1	57.0	44.6	36.3	-8.3 / -10 / 5
NW	*OBS*	*HIST*	*RCP 8.5*	*Δ (RCP - HIST)*
Cat 5	9.7	1.7	20.1	18.4 / 12 / 25
Cat 4	5.9	1.2	6.1	4.9 / 1 / 10
Cat 3	12.1	2.9	12.2	9.3 / 1 / 14
Cat 2	10.9	5.0	15.6	10.6 / 3 / 15
Cat 1	18.4	12.4	25.3	12.9 / 2 / 20
NGP	*OBS*	*HIST*	*RCP 8.5*	*Δ (RCP - HIST)*
Cat 5	27.2	2.2	26.8	24.6 / 4 / 35
Cat 4	7.8	1.9	9.0	7.2 / 0 / 14
Cat 3	20.2	5.0	16.4	11.4 / 2 / 21
Cat 2	23.6	8.7	19.2	10.5 / 2 / 14
Cat 1	33.6	19.4	28.4	9.0 / 2 / 15
GL	*OBS*	*HIST*	*RCP 8.5*	*Δ (RCP - HIST)*
Cat 5	3.3	1.4	30.5	29.1 / 10 / 39
Cat 4	3.2	1.9	13.3	11.4 / 5 / 16
Cat 3	14.4	6.6	23.7	17.1 / 4 / 25
Cat 2	26.8	13.5	25.5	12.0 / 5 / 15
Cat 1	46.4	30.3	32.5	2.2 / -4 / 9
NE	*OBS*	*HIST*	*RCP 8.5*	*Δ (RCP - HIST)*
Cat 5	2.1	0.9	21.4	20.5 / 10 / 32
Cat 4	2.1	1.4	10.7	9.3 / 1 / 14
Cat 3	10.1	6.0	20.3	14.3/ 2 / 21
Cat 2	19.6	13.5	23.5	10.0 / -4 / 20
Cat 1	37.8	36.1	32.3	-3.7 / -13 /

Figure 3-1. Number of days annually with daily maximum WBGT in each category for each location, using the observed station data (O), historical BCCA (H) for 1950-1999, and RCP 8.5 (R) for 2070-2099, averaged over all 12 GCMs for the locations in the seven U.S. regions.

Southwest



Southern Great Plains

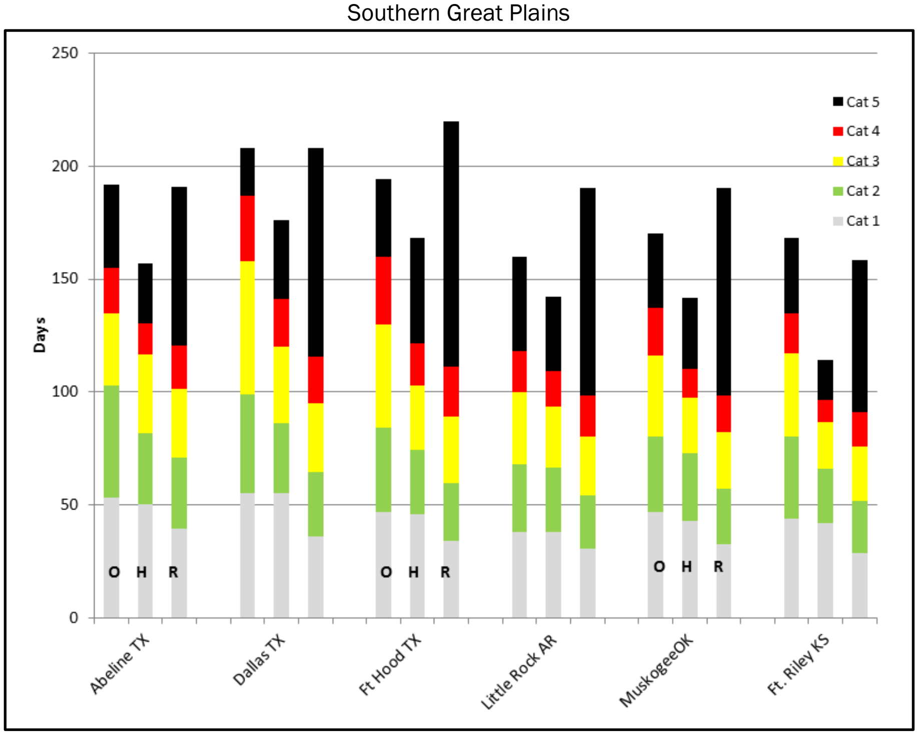
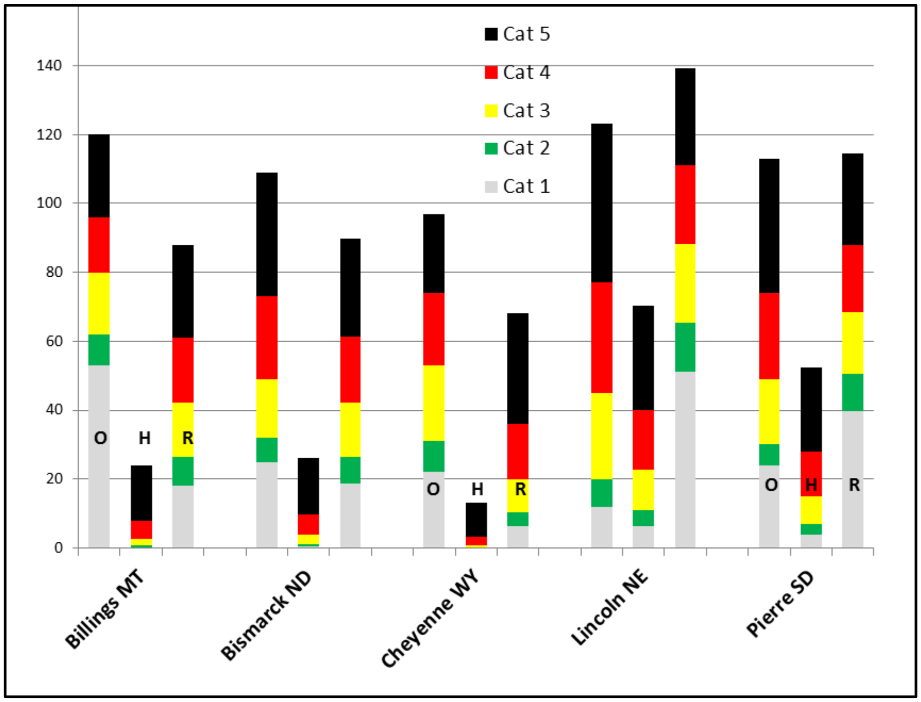


Figure 3-1. Cont'd.

Northern Great Plains



Southeast

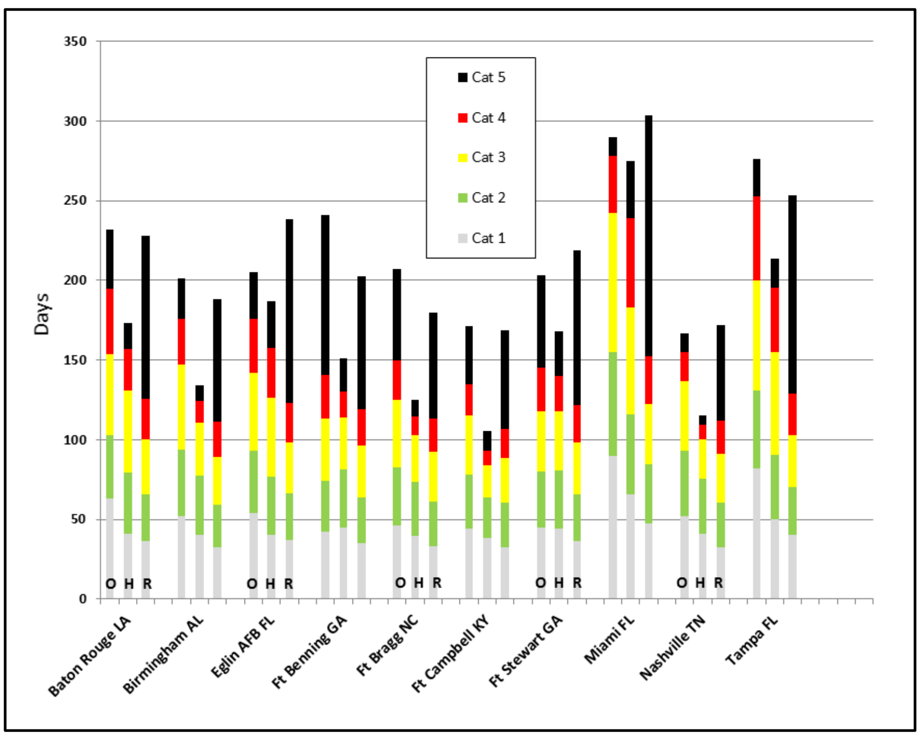
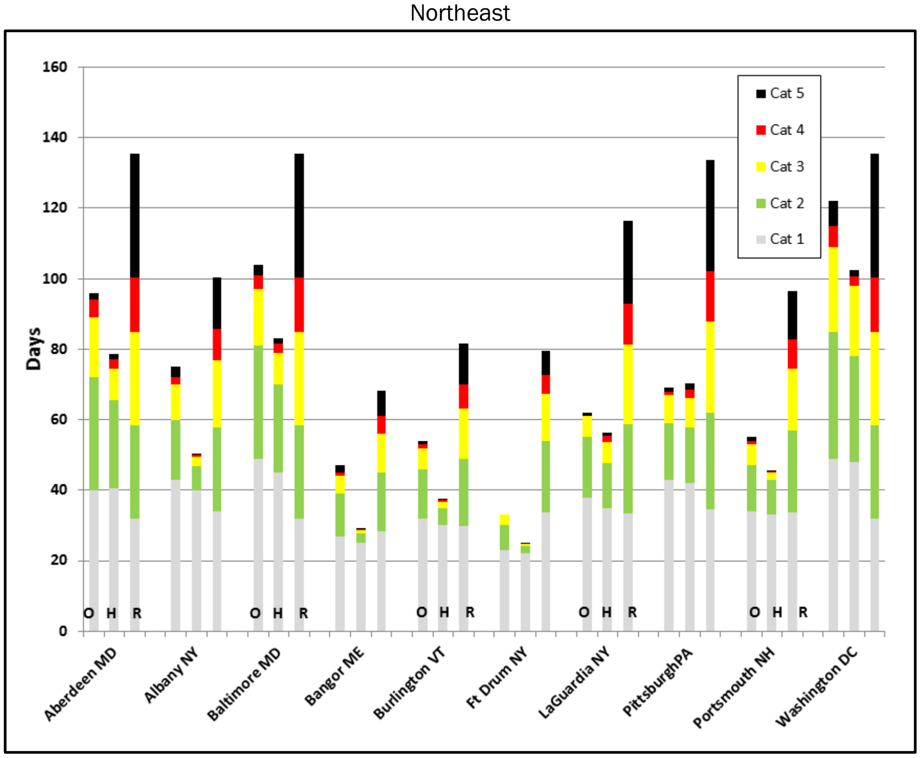


Figure 3-1. Cont'd.



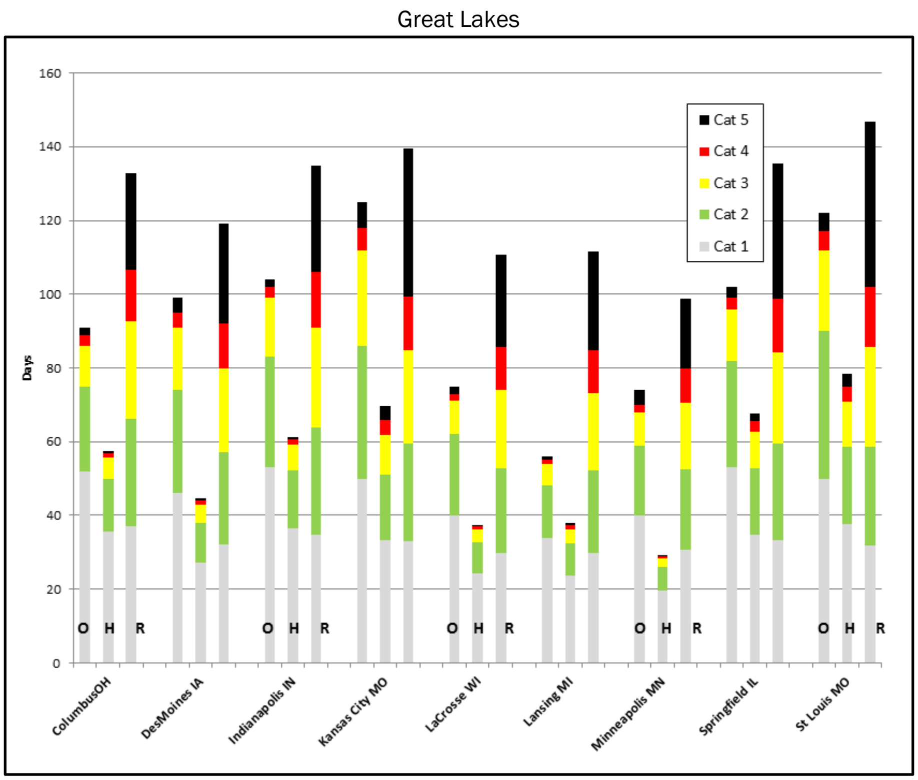
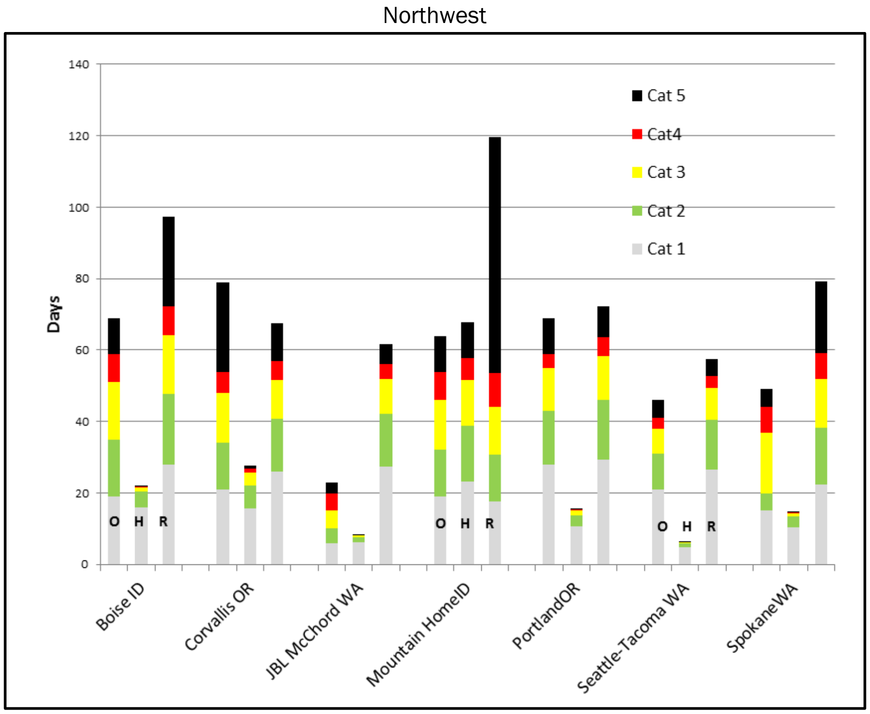


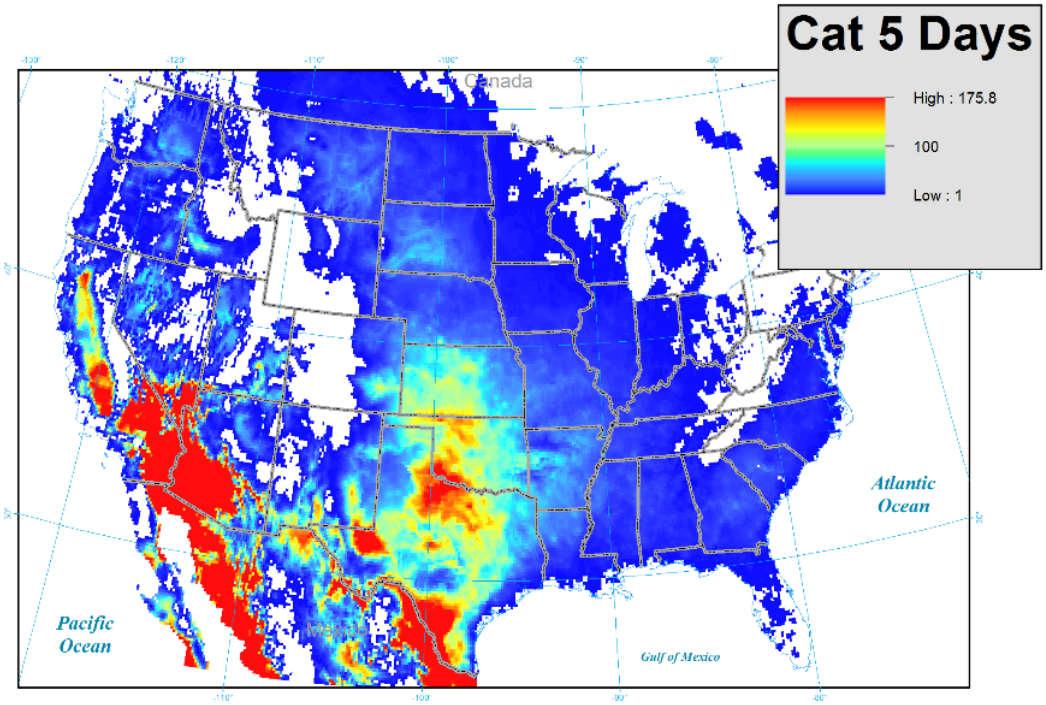
Figure 3-1. Cont'd.



The CONUS-wide maps of the annual days with WBGT in Category 5 (>32 °C [90 °F]) show a substantial increase between the historical data (1950-1999) and the RCP 8.5 projections (2070-2099) (Figure 3-2). There are as many as 124 days per year longer across the southern central plains and Gulf Coast regions, with 60 days longer in the central plains and central California. This represents a significant expansion of the duration of the extreme heat-affected season for Army training bases, particularly for training activities that rely on outdoor training in daylight hours to accomplish their training mission. The Category 5 training restrictions in the Army TB Med (2005) guidance call for 10 minutes training/50 minutes rest for the "Hard Work" activities, such as training for field assaults and walking a hard surface with a 40 lb. load. For the majority of the southern United States, this restriction extends for more than 100 days.

The heat stress restrictions are substantially less during nighttime hours, of course, when large amounts of physical training are conducted outside the peak hours for present-day schedules. The WBGT at the nighttime minimum reaches the lowest Category 1 (<28 °C [82 °F]) for areas in the southern plains and southeast United States (not shown here), but the restrictions on training are considerably less than they are in the daytime.

Figure 3-2. Annual average number of days with the daily maximum WBGT in Category 5 (>32.2 °C [90 °F]) for: (top) HIS data 1950-1999, (middle) RCP data 2070-2099, and (bottom) difference between RCP 2070-2099 and HIS 1950-1999, averaged over the 12 downscaled GCMs.



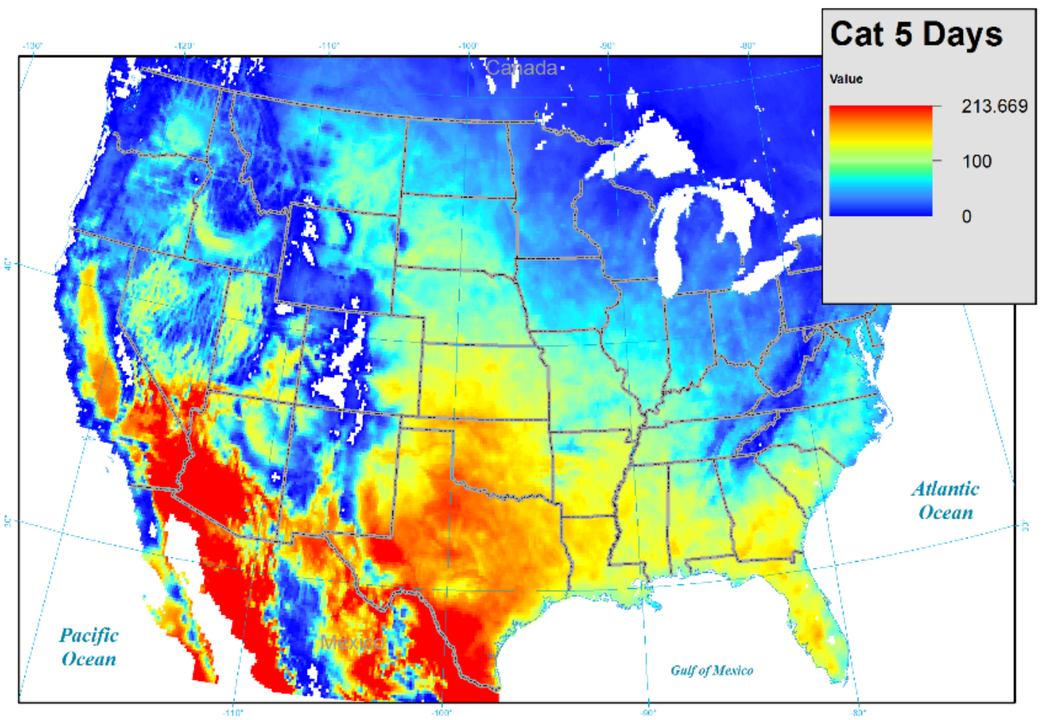
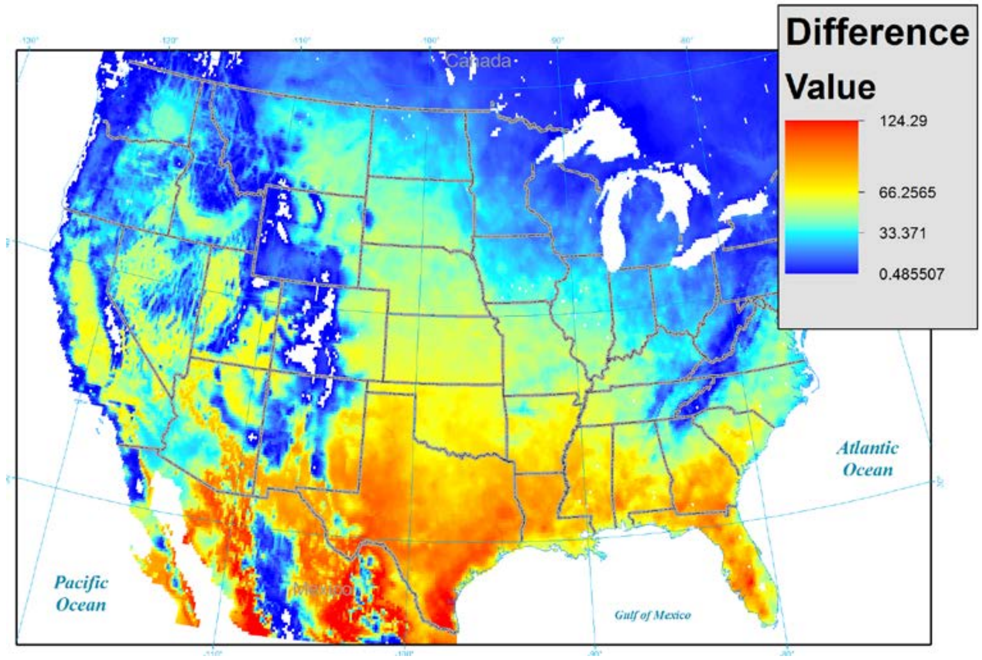


Figure 3-2. Cont'd



3.2 Drought and fire risk

The combined impacts of low-precipitation and high temperatures produce additional risk factors for drought and fires on Army installations, particularly training ranges and across natural resources. Drought conditions carry the risks of reduced water resources for installations, water stress on natural (and landscape) vegetation, and higher fire risks, both in natural wildfires and on live-fire training ranges, as ignited by munitions, tracer rounds, smoke markers, etc.

This study computed the KBDI (Keetch and Byram 1968) that was developed for wildfire risks for the U.S. Forest Service, and that is included as guidance for Army range management in determining whether live-fire exercises might ignite fires, whether they would be contained, or whether they should be restricted from all live-fire training (see Table 3-2).

The KBDI values were computed using the OBS from the locations shown in Figure 2-1, and from the downscaled GCM BCCA projections for the historical period (HIS) 1950-1999, and for RCP 8.5, 2070-2099. Table 3-2 lists the mean days with KBDI in each category for the seven regions, and Figure 3-3 shows those data for the stations in the four driest regions. The days with highest KBDI Category 4 increases by 30 days in the Southwest, 20 days in Southern Great Plains, and 11 days in the Southeast.

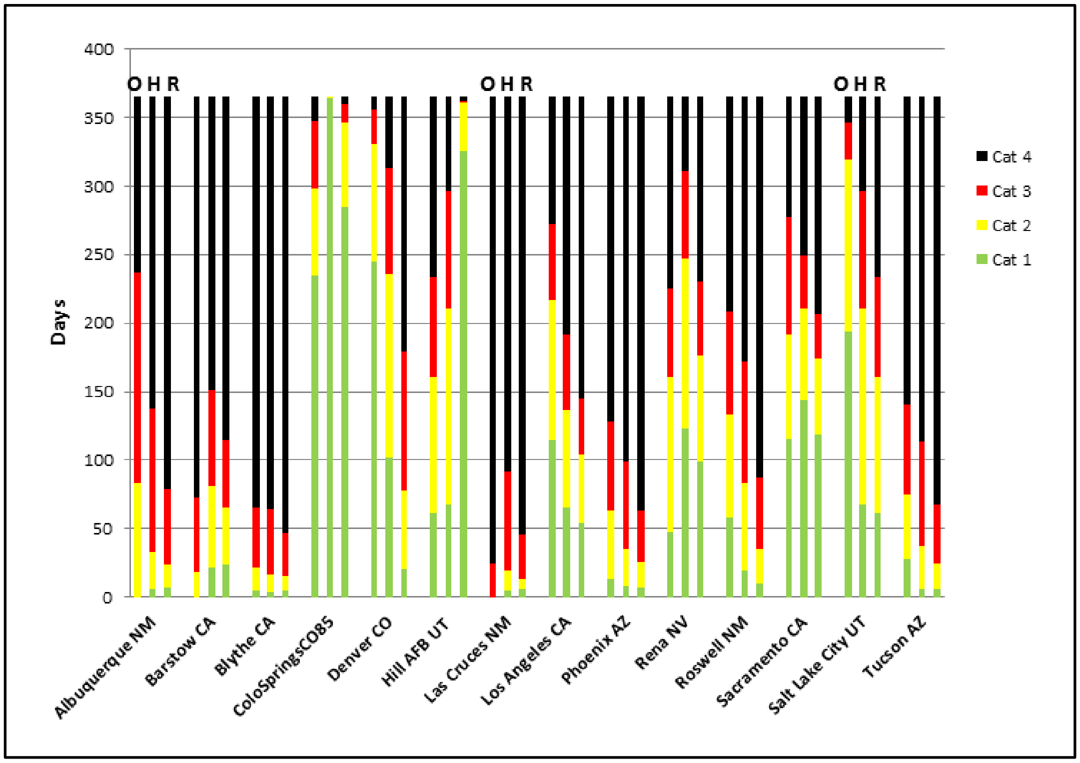
Figure 3-4 shows the region of the greatest increase in KBDI days as the Northern Great Plains. This region, along with the central plains and Ohio Valley, expands significantly in warm dry days, so the increase in drought- and fire-risk expand greatly there, where it has previously been at lower risk. The very dry southwest United States does not get dramatically drier, so the risks there do not change significantly.

Table 3-2. Number of days annually with daily KBDI in each category, using the OBS and historical BCCA (HIST) for 1950-1999, and RCP 8.5 for 2070-2099, averaged over all 12 GCMs for the station locations in the five U.S. regions shown, and the inter-model mean, minimum, and maximum difference in KBDI days between HIST and RCP 8.5.

SW	*OBS*	*HIST*	*RCP 8.5*	*Δ (RCP - HIST)*
Cat 4	155.4	161.3	206.4	45.1 / 32 / 61
Cat 3	61.6	66.2	44.1	-22.1 / - 30 / -10
Cat 2	68.2	65.6	41.1	-24.5 / -32 / -18
Cat 1	79.8	71.9	73.4	1.5 / -5 / 4
SGP	*OBS*	*HIST*	*RCP 8.5*	*Δ (RCP - HIST)*
Cat 4	24.3	78.7	142.9	64.2 / 20 / 70
Cat 3	28.5	46.7	58.1	11.4 / 1 / 22
Cat 2	81.4	80.0	77.6	-2.4 / -21 / 11
Cat 1	230.7	159.6	86.3	-73.3 / -80 / -40
SE	*OBS*	*HIST*	*RCP 8.5*	*Δ (RCP - HIST)*
Cat 4	95.9	128.3	200.3	72.0 / 11 / 89
Cat 3	45.9	53.6	45.2	-8.4 / -22 / 10
Cat 2	64.3	62.3	46.7	-15.6 / -25 / 5
Cat 1	158.9	120.7	72.8	-48.0 / -55 / -15
GL	*OBS*	*HIST*	*RCP 8.5*	*Δ (RCP - HIST)*
Cat 4	29.3	7.8	77.1	69.3 / 15 / 82
Cat 3	19.8	11.1	47.5	36.4 / 12 / 45
Cat 2	56.5	39.5	86.0	46.5 / -5 / 58
Cat 1	259.4	306.6	154.4	-152.3 / - 175 / - 90
NGP	*OBS*	*HIST*	*RCP 8.5*	*Δ (RCP - HIST)*
Cat 4	49.6	6.4	109.4	103.0 / 30 / 125
Cat 3	58.3	16.4	92.5	76.1 / 23 / 99
Cat 2	58.3	16.4	92.5	76.1 / 20 / 89
Cat 1	198.8	325.8	70.5	-255.3 / - 288 / -199

Figure 3-3. Number of days annually with KBDI in each category, using the observed station data (O) 1950-1999, HIS data (H) 1950-1999, and RCP 8.5 data (R) 2070-2099, averaged over all 12 GCMs, for the stations with highest KBDI.

Southwest



Southern Great Plains

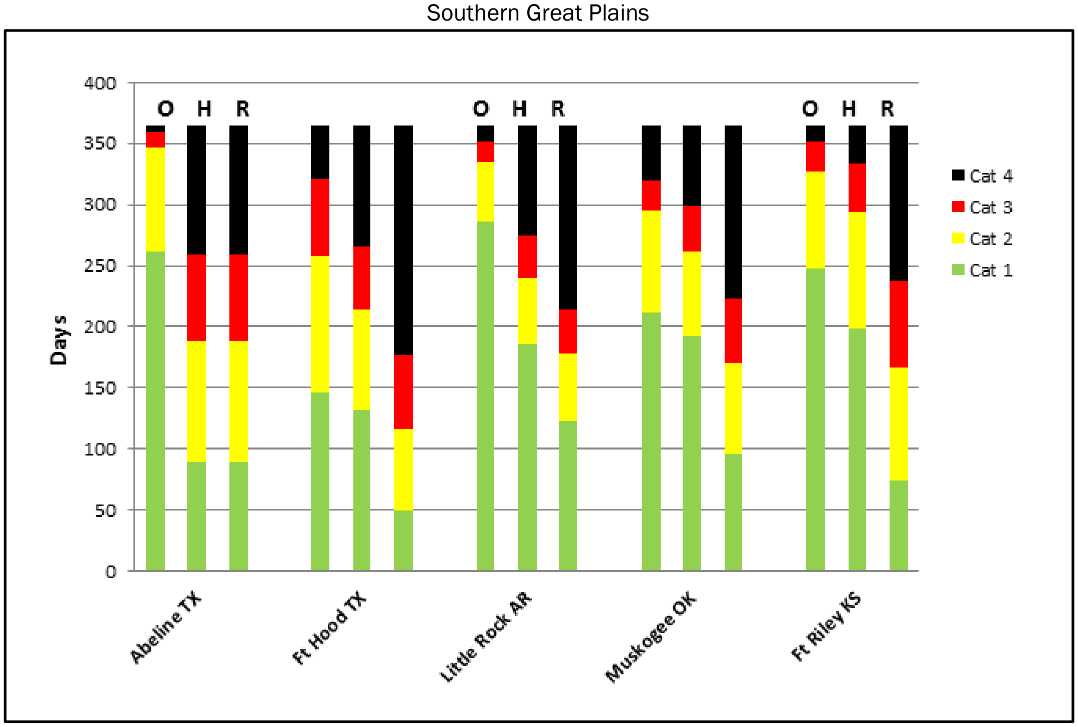
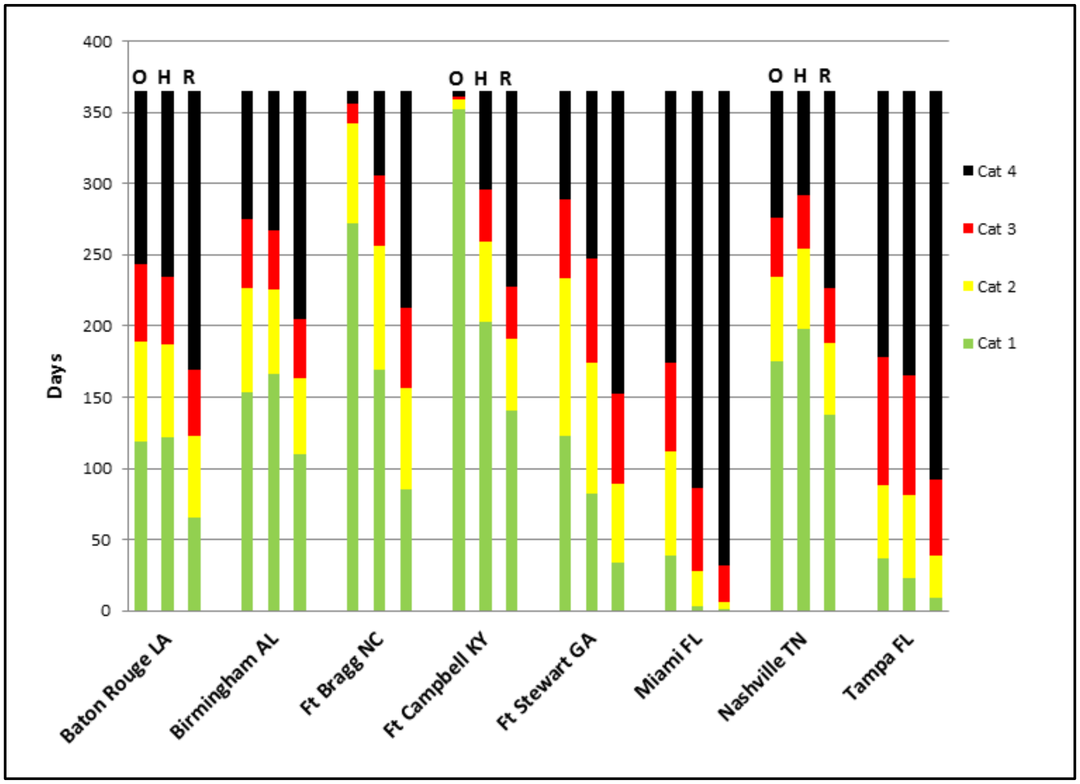


Figure 3-3. Cont'd.

Southeast



Great Lakes and Northern Great Plains

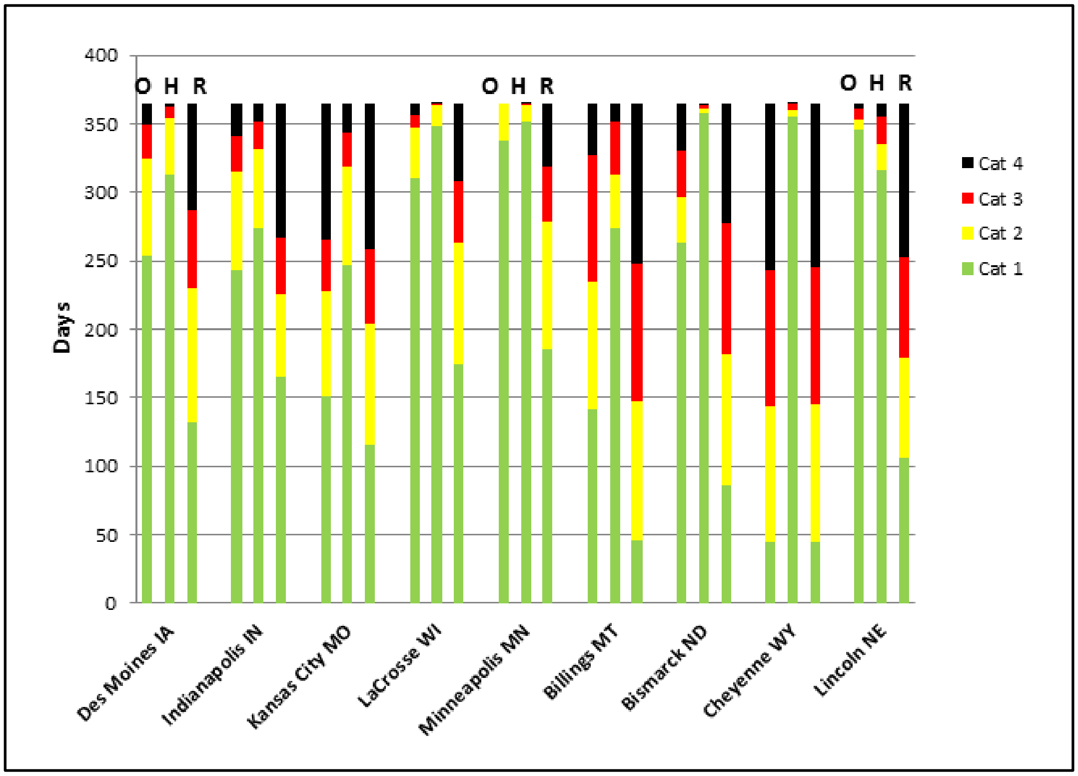
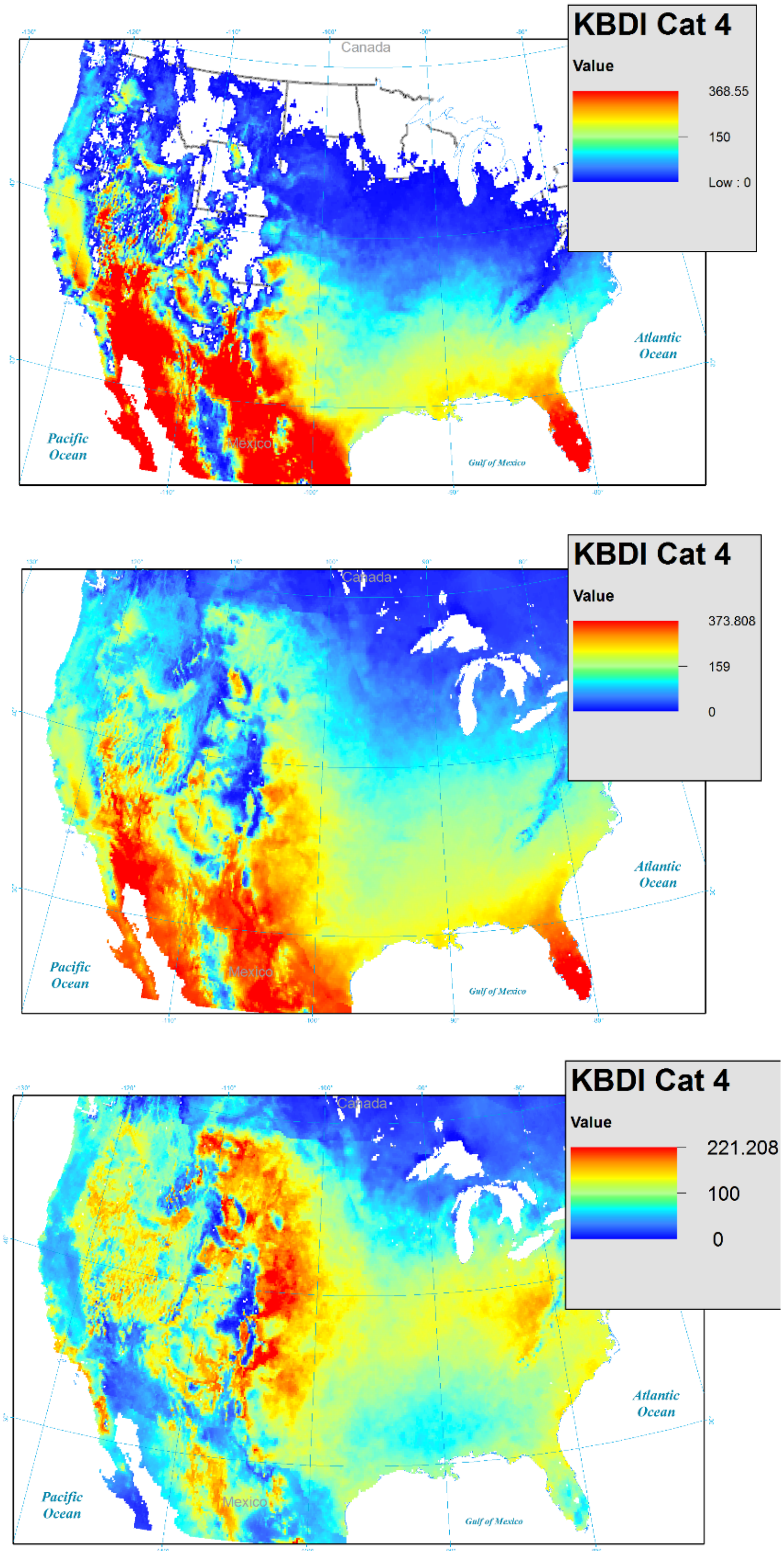


Figure 3-4. Number of days annually with the KBDI in Category 4 (750 to 800) for: (top) HIS data 1950 to 1999, (middle) RCP data 2070 to 2099, and (bottom) difference between RCP 2070-2099 and HIS 1950-1999, averaged over the 12 downscaled GCMs.



3.3 Other climate indices and extremes

The additional climate indices that have been computed from the daily bias-corrected downscaled (BCCA) GCM data include the annual heating and cooling degree-days, These indices represent potential impacts of climate that includes energy usage on Army installations, extreme heat and freeze/thaw impacts on infrastructure (roadways and railways), and water resources and water stress for vegetation on training lands.

The annual HDD for the historical (HIS) data from the 12 downscaled GCMs for 1950 to 1999, RCP 8.5 data for 2070 to 2099, show that the HDD decreases as much as 4000 °F-days (approx. -25% of observed) in the central and northern Rockies, and by 2000-3000 (up to -50%) across the northern United States (Figure 3-5), which is a potentially large decrease in energy use/cost in these regions. Some large Army installations are located in the northern United States (such as Fort Wainwright and Fort Richardson, AK; and J.B. Lewis-McChord and Fort Drum, NY), but not as many as in the southern United States

The other side of this story is the larger increase in the CDD (Figure 3-6), across most of the central and southern United States. The CDD increases by 2500 °F-days (+50% of observed) across the southern United States where many large U.S. Army installations and training ranges are located, and where cooling energy use and costs are substantial.

Figure 3-5. Annual average HDD for: (top) HIS data 1950 to 1999, (middle) RCP 8.5 data 2070 to 2099, and (bottom) difference between RCP 8.5 2070-2099 and HIS 1950-1999, averaged over the 12 downscaled GCMs.

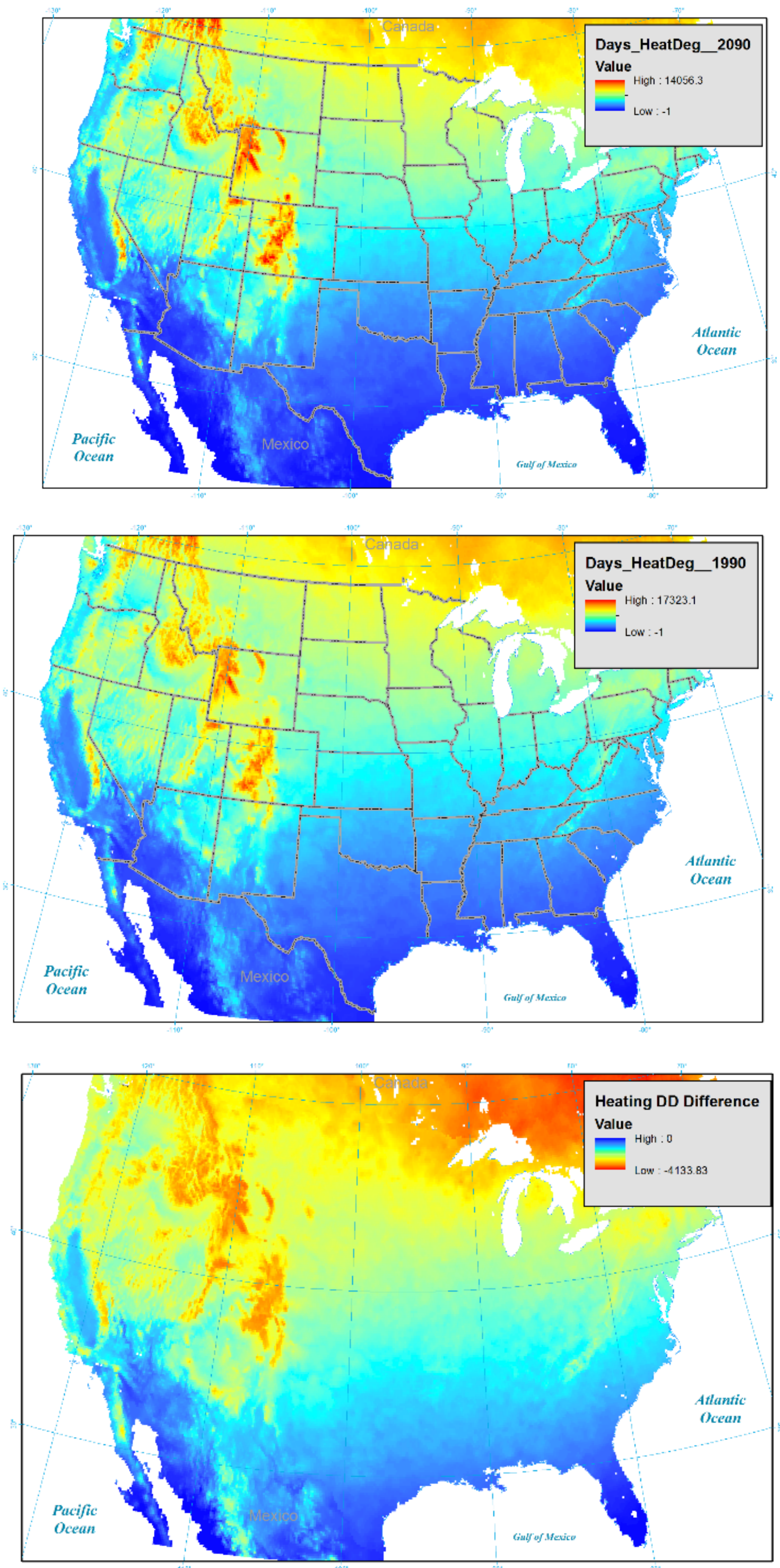
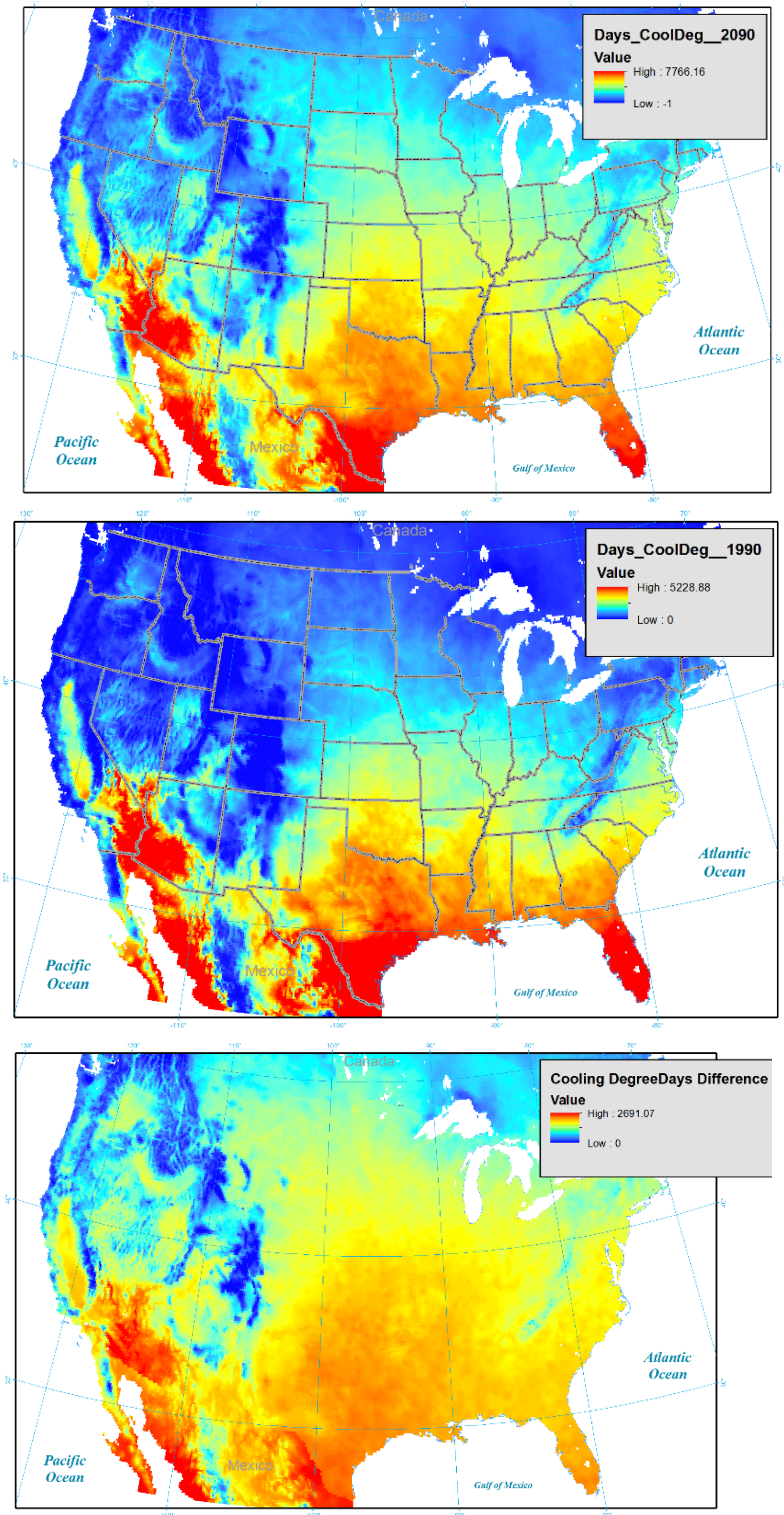


Figure 3-6. Annual average CDD for: (top) HIS data 1950 to 1999, (middle) RCP 8.5 data 2070 to 2099, and (bottom) difference between RCP 8.5 2070-2099 and HIS 1950-1999, averaged over the 12 downscaled GCMs.



Another climate index that represents a significant impact is the number of days where the daily temperatures change from freezing (<0 °C [32 °F]) to non-freezing (>0 °C [32 °F]) or the reverse change, on consecutive days (Figure 3-7). This freezing/melting transition can cause roadways to crack, buckle and create potholes that can both damage vehicles and add to erosion on unpaved roads. The downscale GCM RCP 8.5 data show a projected decrease of up to 14 days of freeze-thaw transitions across the central United States, as the winter season gets shorter overall, but also a northward shift in freeze-thaw days to the northern United States, where normally roads and temperatures would remain below 0 °C (32 °F) for the entire winter.

The occurrences of extremes in precipitation, both high- and low-precipitation extremes, are projected to change under the future RCP 8.5 GCMs on a *regional* basis, rather than according to a CONUS-wide pattern. The days with precipitation greater than 2 in. (Figure 3-8) increase in two main regions; the southeast United States (particularly near the Gulf Coast), and the central and northern west coast, where moisture from the Pacific Ocean drives substantial precipitation in the mountain terrain.

Figure 3-9 shows the number of days with no or low precipitation (less than 0.1 in.), and also a mixed regional signal where much of the western United States and southern Texas coast also increase by up to 19 days, and where the southeast United States and Northern Great Plains decrease by 16 low-precipitation days.

Figure 3-7. Average number of events where the average temperature crosses 0 °C (32 °F) between adjacent days (either increasing or decreasing) for: (top) HIS data 1950 to 1999, (middle) RCP 8.5 data 2070 to 2099, and (bottom) difference between RCP 8.5 2070-2099 and HIS 1950-1999, averaged over the 12 downscaled GCMs.

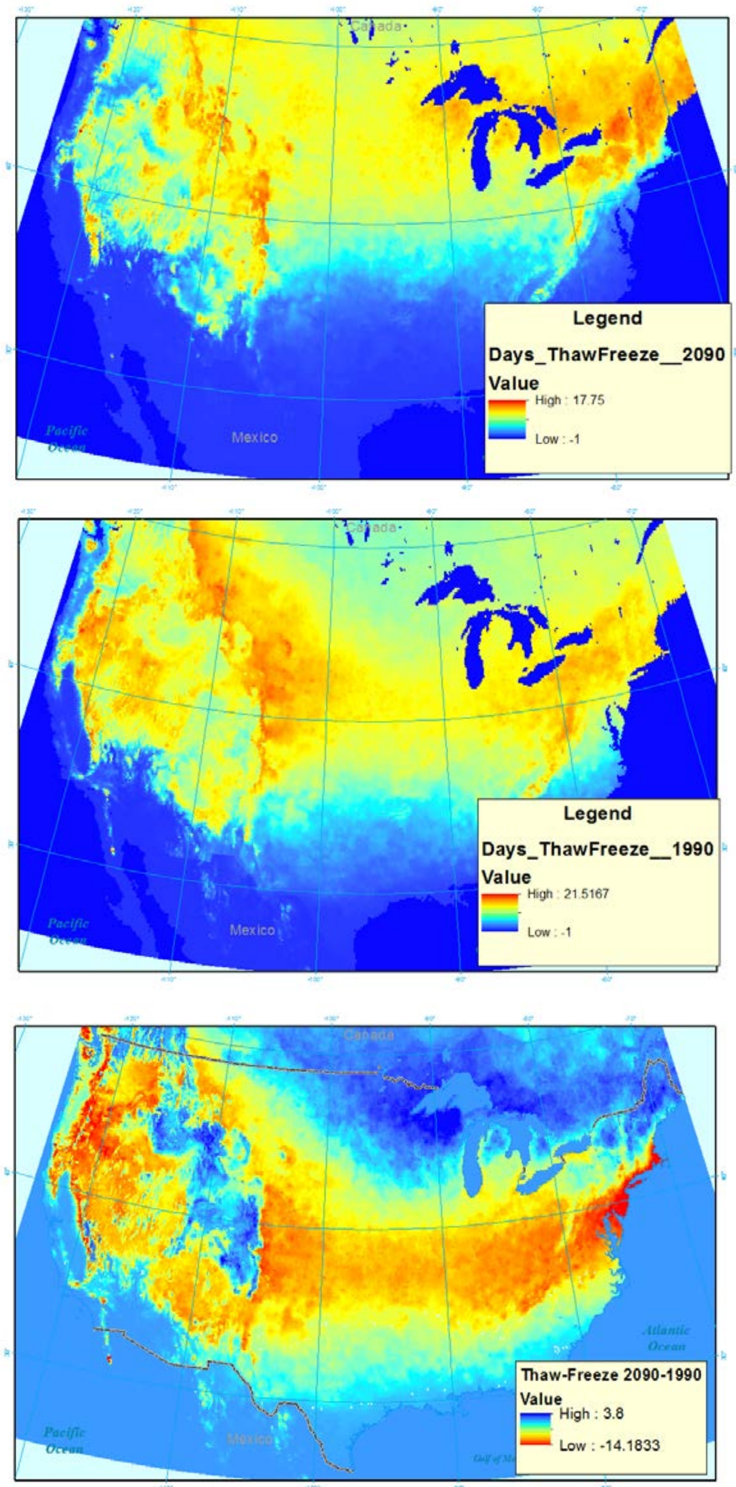


Figure 3-8. Average number of days with daily precipitation greater than 2 in. for: (top) HIS data 1950 to 1999, (middle) RCP 8.5 data 2070 to 2099, and (bottom) difference between RCP 8.5 2070-2099 and HIS 1950-1999, averaged over the 12 downscaled GCMs.

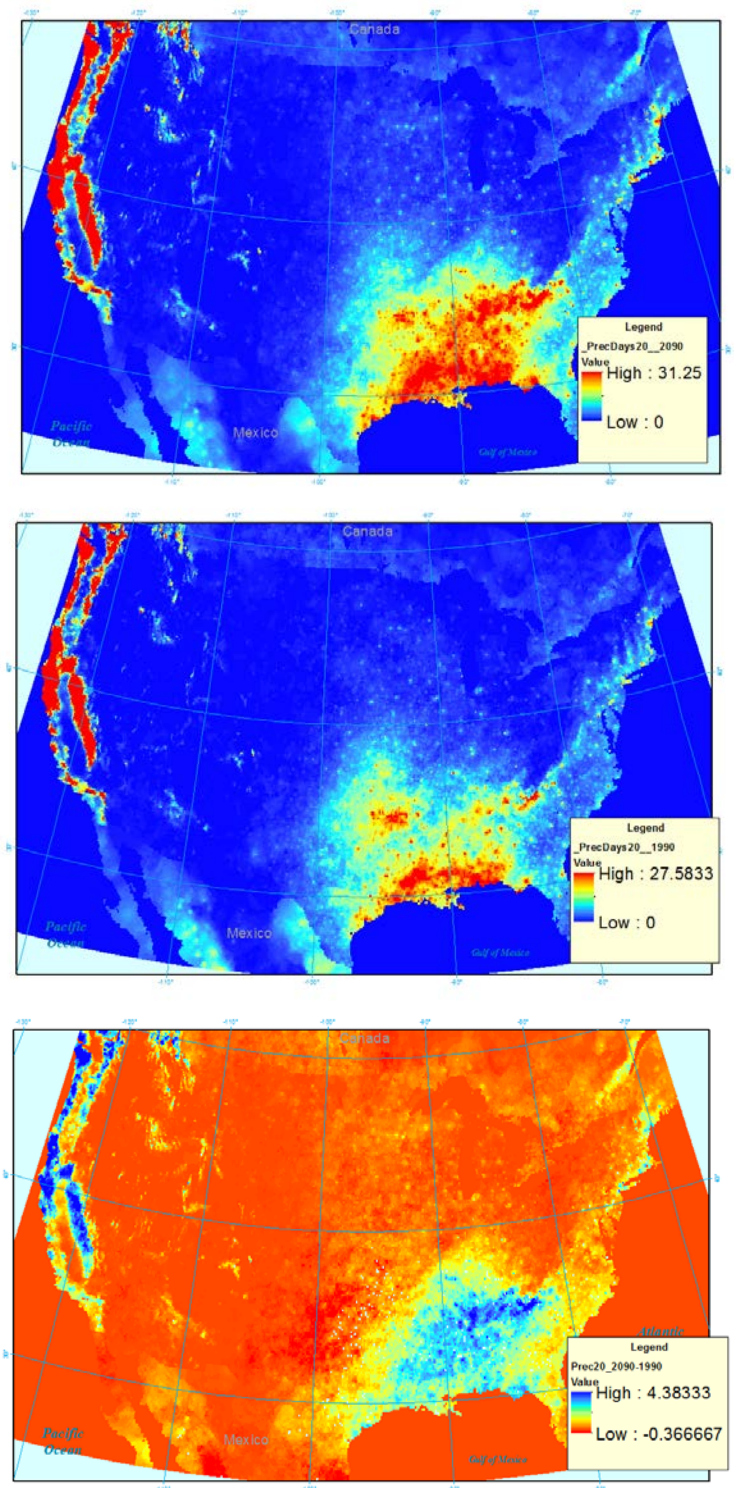
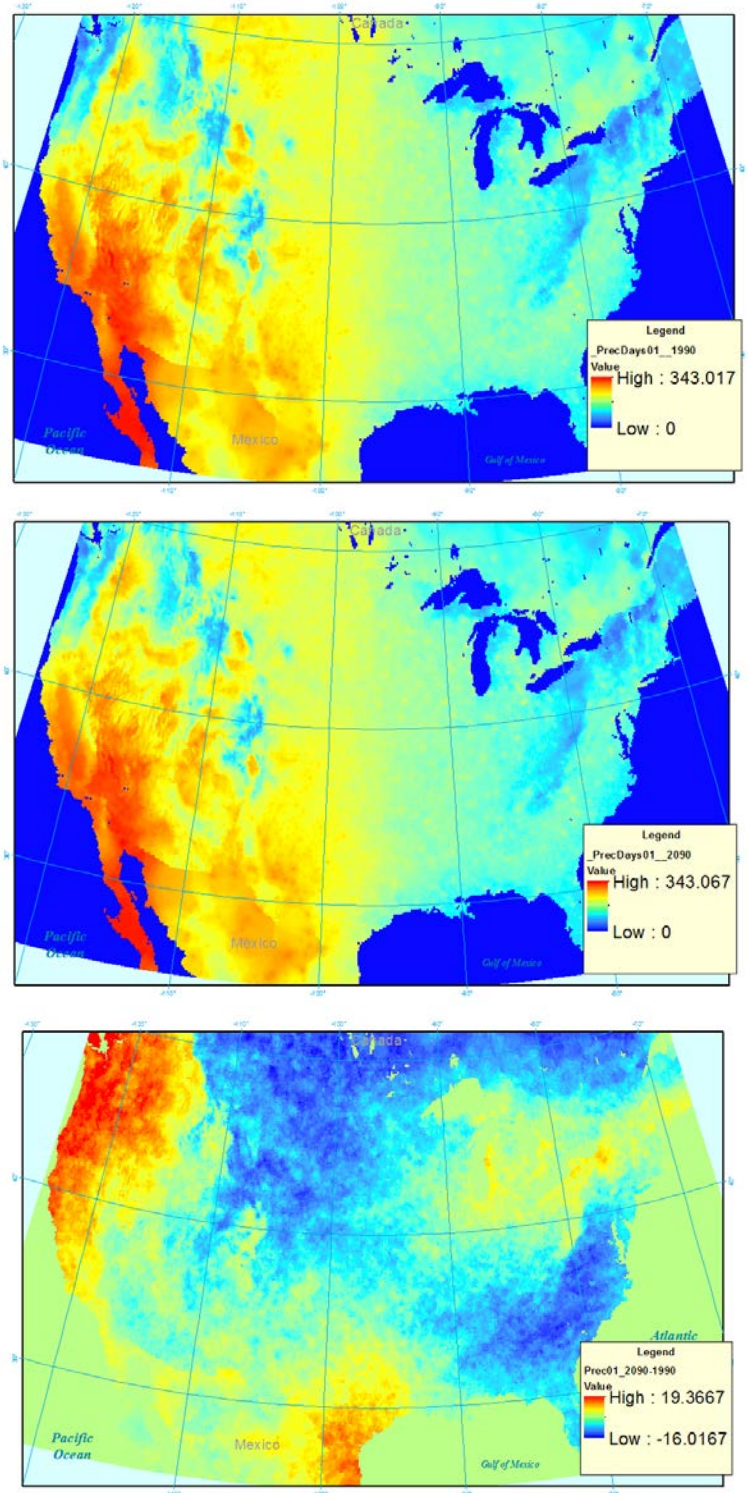


Figure 3-9. Average number of days with daily precipitation less than 0.1 in, for: (top) HIS data 1950 to 1999, (middle) RCP 8.5 data 2070 to 2099, and (bottom) difference between RCP 8.5 2070-2099 and HIS 1950-1999, averaged over the 12 downscaled GCMs.



4 Summary

This analysis of observed and future scenarios of climate indices for CONUS-wide data shows several significant impacts for Army installations and training, projected through the years 2070-2099:

1. Daytime maximum temperatures and extreme heat stress (WBGT >32 °C [90 °F]) for soldiers in training will increase an additional 60 to 120 days a year across most of the southern half of the United States.
2. Nighttime minimum temperatures and heat stresses in the lower category (WBGT <28 °C [82 °F]) also increase across the southern United States, but with much less expected impact on training restrictions.
3. High drought index (associated high fire risk) increases by 60 to 100 days, greatest in the corridor through the Southern and Northern Great Plains, east of the Rockies.
4. Heating degree days decrease by 25 to 50%, with the greatest decrease in the northern United States.
5. Cooling degree-days increase by 50 to 100%, with the greatest increase in the Southern United States.

The potential impacts of these future climate indices on Army installations and the training mission have several key features:

1. Extension of daytime heat-restricted training across most of the southern half of the United States for more than half of the calendar year.
2. Increased durations of the fire-risk season on training ranges in the western plains, which will also expand into the central and Ohio Valley regions.
3. High precipitation events that will lead to greater erosion in the western coastal/mountains of the United States.
4. Increased cooling energy use/cost in most of the southern United States, and decreased heating energy use/cost in the northern United States.
5. Reductions in freeze/thaw cycling damage in the southern central regions due to a shorter winter season.

The Army can potentially adapt to many of these climate changes over time, because it can shift the time of day, season, or location of some kinds of outdoor training away from the most extreme conditions. However, not all training in preparation for real-world conditions can be conducted in low-risk environments; the acclimatization to the appropriate operational climate is an expected part of soldier training. There are limits, however, to known human habitability, i.e., it is not known if humans can physiologically survive in wet bulb temperatures above 35 °C (95 °F). The deadliest heat waves in recorded history (in 1901, 1936, 1950s, 1980) killed over 1000 people in the United States, over 10,000 people in Europe, and over 10,000 people in Asia.

Army installations will need adapt to the increasing costs of cooling in terms of energy usage and costs through budget planning, onsite energy generation, and implementation of net-zero energy projects.

The high fire risks for Army training ranges can be managed through the use of prescribed burning programs that reduce the available fuel for wildfires, and by limiting live-fire training to periods of relatively low fire risk.

Acronyms and Abbreviations

Term	Definition
AFB	Air Force Base
ANSI	American National Standards Institute
BCCA	Bias-Corrected Climate Analog
BOM	Bureau of Meteorology (Australia)
CDD	Cooling Degree Days
CEERD	U.S. Army Corps of Engineers, Engineer Research and Development Center
CMIP	Coupled Model Intercomparison Project
CNRM	Centre National de Recherches Meteorologiques
CRREL	Cold Regions Research and Engineering Laboratory
CSIRO	Australia's Commonwealth Scientific and Industrial Research Organization
DoD	U.S. Department of Defense
ERDC	Engineer Research and Development Center
ERDC-CRREL	Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory
ESM2M	Earth System Model
GCM	Global Climate Model
GHG	Greenhouse Gas
GIS	Geographic Information System
GL	Great Lakes
HDD	Heating Degree Day
HIS	Historical?? (Data)
HIST	historical BCCA (data)
HQDA	Headquarters, Department of the Army
HQUSACE	Headquarters, U.S. Army Corps of Engineers
INM	Institute for Numerical Mathematics
IPCC	Intergovernmental Panel on Climate Change
IPSL	Institut Pierre-Simon Laplace
KBDI	Keetch-Byram Drought Index
MPI-M	Max-Planck-Institut for Meteorology
MRI	Meteorological Research Institute
NGP	Northern Great Plains
NOAA	National Oceanic and Atmospheric Administration
NSN	National Supply Number
OBS	Observed Station Data
OMB	Office of Management and Budget
RCP	Representative Concentration Path
RH	Relative Humidity
SAR	Same As Report
SE	Southeast

Term	Definition
SF	Standard Form
SGP	Southern Great Plains
SW	Southwest
TB	Technical Bulletin
U.S.	United States
UK	United Kingdom
USA	United States of America
USDA	U.S. Department of Agriculture
WBGT	Wet Bulb-Black Globe Temperature
WCRP	World Climate Research Programme

References

Bureau of Reclamation. 2014. Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections, http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html#About

Christensen, J. H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R. K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C. G. Menéndez, J. Räisänen, A. Rinke, A. Sarr, and P. Whetton. 2007. Regional climate projections. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY: Cambridge University Press.

Crane. W. J. B. 1982. Computing grassland and forest fire behaviour relative humidity and drought index by pocket calculator. *Australian Forestry*. 45(1):89-97.

Headquarters, Department of the Army (HQDA). 2003. *Heat Stress Control and Heat Casualty Management*. Army Technical Bulletin Medical 507 (TB MED 507). Washington DC: HQDA, http://armypubs.army.mil/med/dr_pubs/dr_a/pdf/tbmed507.pdf

Intergovernmental Panel on Climate Change (IPCC) 2013: Climate change 2013: The physical science basis. *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley, eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

———. 2007. Climate change 2007—The physical science basis. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom: Cambridge University Press, http://www.ipcc.ch/ipccreports/ar4-wg1.htm

Keetch. J. J., and G. M. Byram. 1968 (rev. 1988). *A Drought Index for Forest Fire Control*. Research Paper SE-38. Asheville NC: U.S. Department of Agriculture (USDA) Forest Service, Southeastern Forest Experiment Station.

Maurer, E. P., L. Brekke, T. Pruitt, and P. B. Duffy. 2007. Fine-resolution climate projections enhance regional climate change impact studies. *Eos, Transactions of the American Geophysical Union* 88(47):504.

Mearns, L. O., W. J. Gutowski, R. Jones, L.-Y. Leung, S. McGinnis, A. M. B. Nunes, and Y. Qian. 2009. A regional climate change assessment program for North America. *Eos, Transactions of the American Geophysical Union* 90(36):311-312.

Meehl, G. A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J. F. B. Mitchell, R. J. Stouffer, and K. E. Taylor. 2007. The WCRP CMIP3 multi-model dataset: A new era in climate change research. *Bulletin of the American Meteorological Society* 88(9):1383-1394.

Melillo, J. M., T. C. Richmond, and G W. Yohe, eds. 2014. *Climate Change Impacts in the United States: The Third National Climate Assessment*. U.S. Global Change Research Program. doi 10.7930/JOZ31WJ2.

Nakicenovic, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grübler, T. Y. Jung, T. Kram, E. L. La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor, and Z. Dadi. 2000. *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK, http://www.grida.no/climate/ipcc/emission/index.htm

Pal, J. S., and E. A. B. Eltahir, 2016: Future temperature in southwest Asia projected to exceed a threshold for human adaptability. *Nature Climate Change* 6, doi 10.1038/NClimate2833.

Weatherly, J. W., and M. A. Rosenbaum, 2017: Future projections of heat and fire-risks for the contiguous United States. *Journal of Applied Meteorology and Climatology*, doi http://dx.doi.org/10.1175/JAMC-D-16-0068.1

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14. ABSTRACT
Increasing temperatures and changes in precipitation associated with climate change are expected to have increasing impacts on the contiguous United States in the coming decades, including impacts on military training and outdoor activities in general. This work used projections of daily temperature and precipitation from multiple global climate model projections to calculate the days with high heat and drought indices, extreme high- and low temperature and precipitation event days, and heating and cooling degree-day indices. The heat stress index (the wet bulb black globe temperature, or WBGT) and Keetch-Byram drought index are calculated from climate model projections from 1950-1999 and 2070-2099, and compared to projections calculated from observed weather data for stations across the contiguous United States. Results showed that significant increases are projected across the southern United States for the days in the high heat category above 32 °C (90 °F). The higher humidity of the southeastern United States contributes to high WBGT as well, while the air temperatures are greatest in the southwest. These projected impacts can be characterized as widespread and severe for large portions of the United States, with expected impacts to military planning, public health and safety, and natural resource management.

15. SUBJECT TERMS
Climatic changes--Risk assessment, Climatic changes—Forecasting, Climatic changes--Research--United States, Military bases

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